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Application of Passive Porous Treatment to Slat Trailing Edge Noise

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Abstract

Porous trailing-edge treatment is investigated as a passive means for slat noise reduction by using time-accurate simulations based on Reynolds-averaged Navier-Stokes equations. For the model scale high-lift configuration used during previous experiments in the Low-Turbulence Pressure Tunnel at NASA Langley Research Center, application of the proposed treatment over a minute fraction of the slat surface area is shown to mitigate the noise impact of the trailing edge, with no measurable aerodynamic penalty. Assessment of the pressure fluctuations in the vicinity of the treated edge indicates a potential noise reduction in excess of 20 dB. The primary mechanism underlying this reduction is related to the reduced strength of Strouhal shedding from the finite thickness trailing edge. A secondary effect of the treatment involves an upward shift in the Strouhal-shedding frequency to a frequency band of reduced auditory sensitivity in a full-scale application.

Introduction

To facilitate future growth in air transportation while ensuring compliance with the increasingly stringent noise regulations, researchers must investigate noise prediction and reduction technologies. Communities adjacent to major airports are often exposed to high noise levels from airframe-generated sound from commercial airliners. Airframe noise is most pronounced during aircraft approach and landing, when engines are operating at reduced thrust and additional airframe components, such as high-lift devices, are deployed. Sound radiated from the leading-edge slat can be a major component of airframe noise (Dobrzynski et al. 1998; Storms et al. 1998). In wind tunnel experiments carried out by NASA and U.S. industry partners (Macaraeg 1998) as well as at the University of Southampton (Takeda, Ashcroft, and Zhang 2001), the slat trailing edge was found to be a significant contributor to the overall slat noise. In these studies, the slat noise spectrum generally consisted of broadband noise associated with slat-cove unsteadiness and a high frequency hump with relatively large amplitudes (Storms et al. 1999; Olson et al. 2000, 2001; Takeda, Zhang, and Nelson 2002; Mendoza, Brooks, and Humphreys Jr. 2002). Khorrami, Berkman, and Choudhari (2000) determined that the origin of the high frequency peak to be vortex shedding from the finite-thickness trailing edge and its amplification via resonant reflections in the gap region between the slat and the main element (Tam and Pastouchenko 2001; Agarwal and Morris 2002).

Recent wind tunnel investigations reveal that porous treatments over small yet appropriately positioned segments of solid surfaces can lead to considerable reduction in radiated aerodynamic noise from the flap side edge (Revell et al. 1997; Storms et al. 1998). Related computations based on steady Reynolds-averaged Navier-Stokes (RANS) equations (Choudhari and Khorrami 2003) attribute at least a portion of this reduction to a weakening of the flap vortex that is believed to be responsible for a major portion of the flap side edge noise (Streett 1998). However, it is necessary to carry out time-accurate computations of the flap side edge flow field to provide a more complete picture of the physical mechanisms underlying noise reduction via the porous tip treatment and to facilitate optimization of the treatment design. Due to the intrinsic three-dimensionality of this flow field, the resources required for calculations of this type are prohibitively large. Thus, it is useful to first consider numerical implementation of the porous treatment in the context of two-dimensional unsteady flows. The slat noise problem is amenable to two-dimensional simulations as shown by Khorrami, Berkman, and Choudhari (2000) and Singer, Lockard, and Brentner (2000). In this paper we examine the application of the porous treatment to reduce or eliminate the high-frequency tone associated with Strouhal shedding from the slat trailing edge.

A technique that has previously shown promise for reducing trailing-edge noise is *trailing-edge serration*. The serration is applied in the form of a series of identical triangular notches of a specified width and length. It is conjectured that serration partially redirects spanwise vorticity into streamwise vorticity and, therefore, significantly reduces spanwise correlations of the local turbulent fluctuations. Similar reasoning also led to successful reduction of the Strouhal tone from a large aspect-ratio cylinder by wrapping a thin wire around the cylinder in a helical pattern. A porous trailing-edge treatment has also been considered for reducing the broadband noise emitted by compressor blades (Potter 1968); however, only a relatively modest noise reduction (3 dB or less) was noted as a result of this treatment. Moreover, the treated area was large, ranging from 12.5 to 37.5 percent of the blade chord. This large treatment area surely affected the primary aerodynamic function of the blade; however, such effects were not measured or documented.

The present approach applies passive porous treatment to a small, select surface area of a slat trailing-edge region. The porous edge provides a mechanism for flow communication among the slat lower, end, and upper surfaces and therefore allows a modified lift distribution to be established at the trailing edge. The effectiveness of the porous treatment is demonstrated through time-accurate simulations of the unsteady flow past a model high-lift configuration previously used in experimental studies at NASA Langley Research Center. A description of the computational approach and a brief summary of the results are provided in the next section. Concluding remarks are presented in the final section of the paper.

Computational Approach and Results

The effectiveness of the porous trailing-edge treatment is tested on an Energy Efficient Transport (EET) wing (Berkman, Khorrami, Choudhari, and Sadowski 2000). The three-element, high-lift model is composed of a supercritical main element with slat and a flap of chord lengths 15.5 and 30 percent, respectively, compared with the stowed chord of the combined configurations (figs. 1(a) and 1(b)). The trailing edge of the slat is flat with sharp edges and has an approximate thickness of 0.5 mm (i.e., less than 0.5 percent of the slat chord). The angle of attack is 10 degrees, with slat and flap deflection angles of 30 degrees each. The Mach number is 0.2, yielding a Reynolds number of 7.2 million based on the clean airfoil chord. For this configuration, slat noise is known to be dominated by the trailing-edge noise and, therefore, the chosen case is particularly well-suited for demonstrating the effectiveness of the porous treatment. More detailed information about geometry of the model and the associated aerodynamic and acoustic characteristics of the baseline case may be found in Khorrami, Berkman, and Choudhari (2000).

The computer code CFL3D, developed at NASA Langley Research Center (Krist, Biedron, and Rumsey 1998), is used to simulate the effects of treatment on the slat trailing-edge flow field in a time-accurate mode. During such computations, it is neither desirable nor necessary to include the details of the flow in the immediate vicinity of the pores on the treatment surface. Because of the relatively small length scales associated with the pores, the effect of porosity on the overall flow is simulated by prescribing a jump condition that specifies the relation between (area-averaged) flow quantities on both sides of the surface. For the porous segments envisioned for the present application, the magnitude of the area-averaged transpiration velocity is assumed to be sufficiently small and is determined by the local characteristics of the perforated surface. The nondimensional jump condition at any point of the treated surface can thus be expressed as $V_n = (P_{out} - P_{in})/R$, where the normal velocity V_n, pressures P_{out} and P_{in} above and below the surface, and the surface resistivity R refer to local values of the respective quantities. As a first approximation, R is assumed to be a constant. The simplest model for the internal cavity region that is consistent with the hypothesis of an open-area-ratio is to assume that the cavity pressure is uniform, with a value that lies between the minimum and maximum values of pressure over the treated surface. This uniform internal pressure is determined iteratively by imposing the constraint of passive porosity, namely, that the averaged mass flux across the entire porous region is zero. As many as 70 subiterations were used during each time step to ensure that the passivity constraint was satisfied. For similar and more refined implementations of the porous surface boundary condition, the reader may refer to Khorrami, Li, and Choudhari (2002) and Frink et al. (2001), respectively. The modeled porous treatment is applied to the trailing-edge region, specifically on the end surface and on small segments of the pressure and suction surfaces that are adjacent to the edge. The two relevant and adjustable parameters for fine-tuning the effectiveness of the treatment are the streamwise extent of the treated surface area and the coefficient R that determines the resistance of the perforated face sheet. For the present application, the treated surface area on both pressure and suction sides of the slat extend approximately two edge heights forward of the trailing edge (see fig. 2). The resistance, which scales with the flow momentum (due to the hydrodynamic rather than acoustic action of the porous treatment), was fixed at 800 MKS Rayls.

Due to the finite thickness of the slat trailing edge, the boundary layers on the pressure and suction sides of the slat separate near the trailing edge and form free shear layers that roll up and shed strong spanwise vortices in the form of a vortex street. Interaction of the vortex street with the trailing-edge surface produces high-amplitude pressure oscillations that radiate noise to the far field. For a noise reduction technique to be effective, it must either eliminate or significantly diminish the vortex shedding and, in so doing, reduce the intensity of the pressure fluctuations near the slat trailing edge.

Figure 3 illustrates the effects of a significantly diminished vortex shedding process in the case of the treated trailing edge. The peak pressure fluctuation near the bottom corner of the trailing edge is clearly reduced by an order of magnitude after the edge treatment has been turned on. Figures 4(a) and 4(b) demonstrate the consequences of vortex shedding suppression in terms of noise radiation. The range of contours for the baseline and treated cases indicates that the far field noise intensity is likely to be reduced by more than 20 dB. This reduction in sound pressure level is also accompanied by a 25 percent increase in the dominant frequency. Because the shedding frequencies in full-scale configurations are already expected to exceed the range of peak auditory sensitivity, the shift in the dominant frequency will further reduce noise impact because the human ear is less sensitive to the higher frequencies involved.

Discussion and Concluding Remarks

The unsteady computations presented in this paper extend previous work that involved purely stationary computations related to the effects of a porous surface treatment on acoustically relevant features of a high-lift flow field. Specifically, we showed that applying the porous treatment over a minute fraction of the slat surface area could yield an order of magnitude reduction in the noise impact associated with the trailing edge, with no measurable aerodynamic penalty. Because the proposed treatment is passive and does not introduce any geometric complexity, it can easily be retrofitted to the existing airliner fleet and incorporated into future aircraft designs. Numerical simulations like those presented in this paper can provide the necessary details of the unsteady flow field and facilitate the implementation of a highly optimized and viable treatment strategy.

The computations revealed that the porosity–induced noise reduction is attributed to altering the noise source mechanisms rather than attenuation of the radiated noise during the propagation phase. Therefore, contrary to an earlier suggestion by Hayden and Chanaud (1974) that the resistance of the porous surface should scale with the specific acoustic impedance ρc of the fluid (where c denotes the speed of sound), our computations showed that the treatment resistance should scale with respect to the flow momentum ρU_∞ (where U_∞ denotes the free-stream speed), with a numerical coefficient of O(10).

The construction of the porous treatment surface envisioned in this application would involve a finely woven wire mesh surface; alternatively, it could be similar to the surfaces already being used for wall cooling on turbine blades (Moskowitz, 1970) or in some designs of engine duct acoustic treatment. Thus, off-the-shelf materials (with suitably characterized properties) could be employed to transition the porous treatment concept to flight applications, provided only that the designer has sufficient knowledge of the relevant design characteristics such as the location and extent of the treated region and the resistance (or, more generally, the impedance) of the porous surface. With suitable calibration against experimental measurements, numerical simulations could help identify appropriate values for the design parameters in a given application of the porous treatment.

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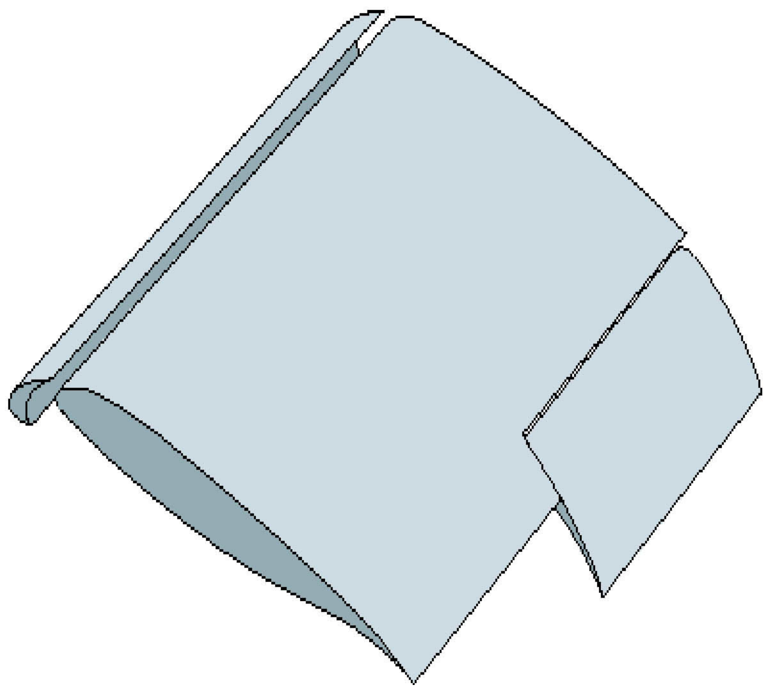
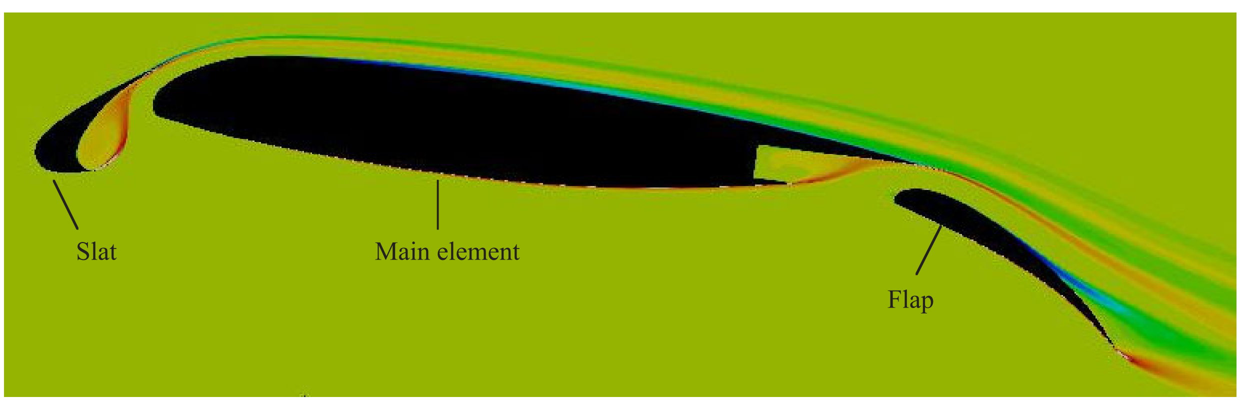


(a) Perspective view.



(b) Side view.

Figure 1. Schematic of three-element high-lift configuration.

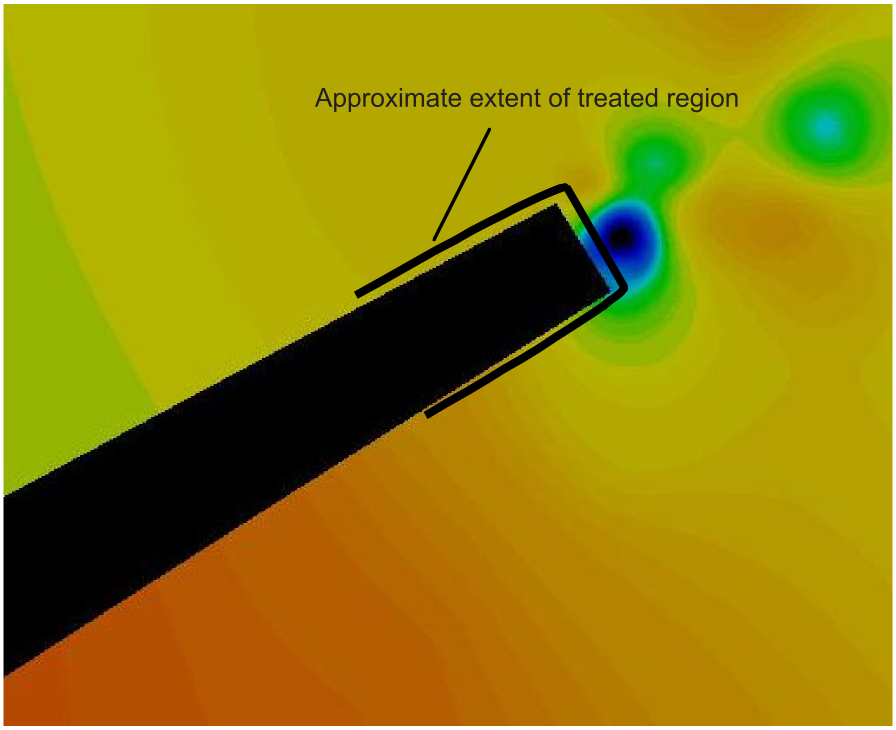


Figure 2. Schematic of treated trailing edge.

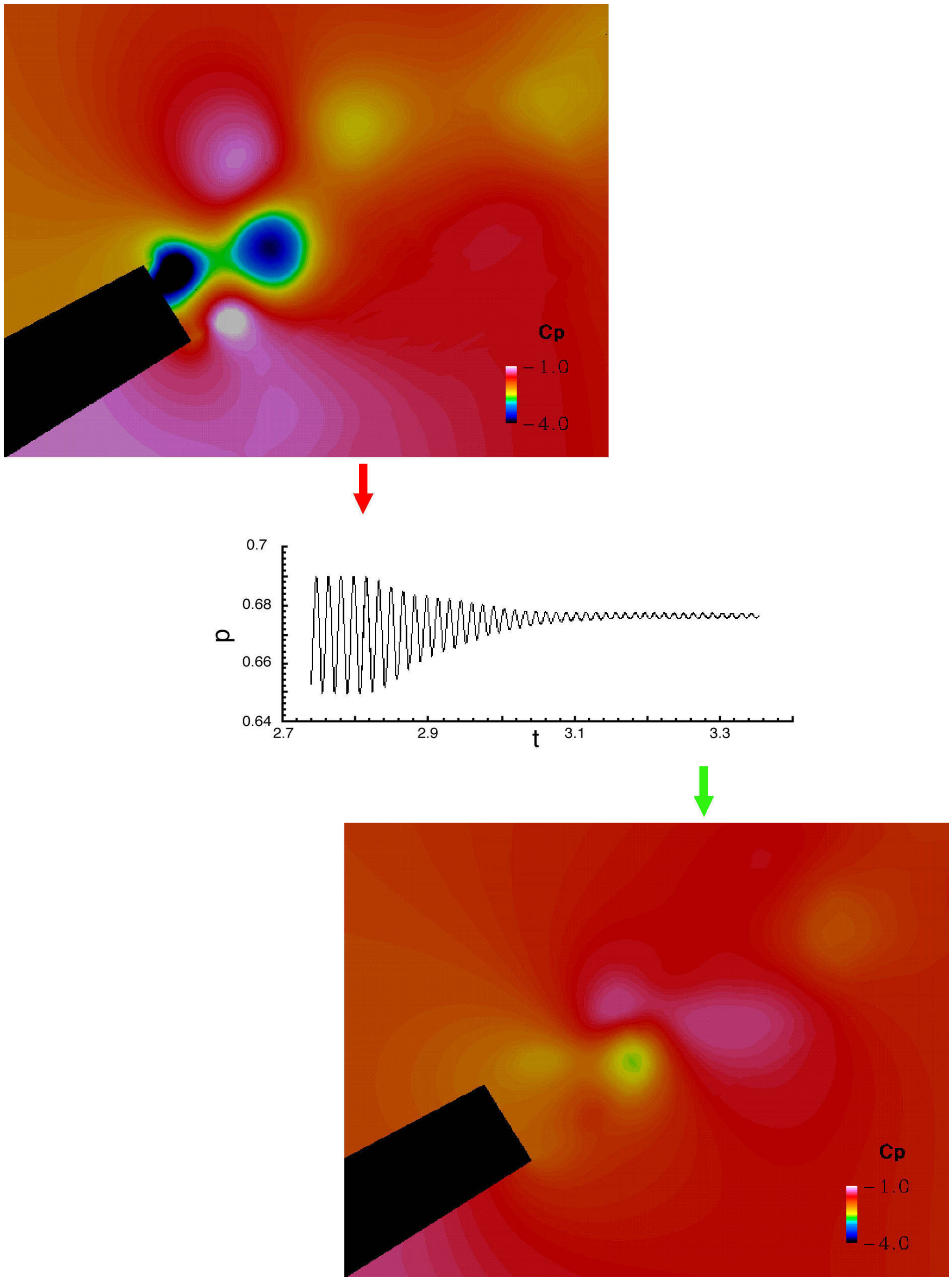
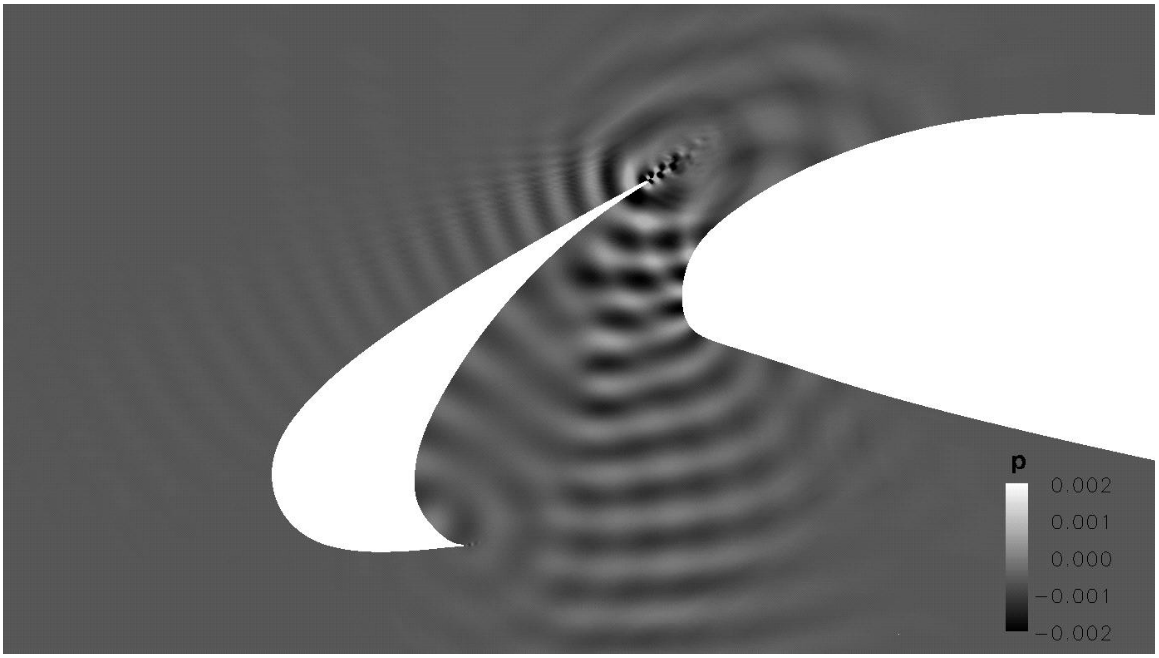
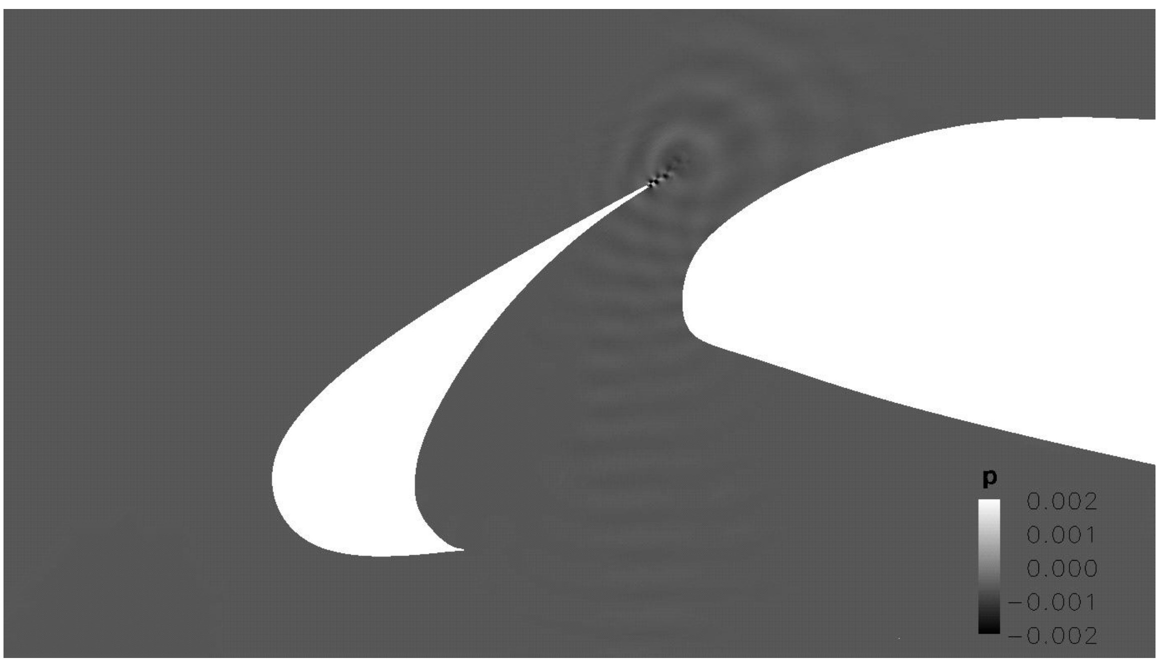


Figure 3. Suppression of vortex shedding via porous trailing edge. Top: pressure contours for untreated case; middle: pressure history near trailing edge (nondimensional pressure p is normalized by ρc^2) ; bottom: treated case.



(a) Untreated case.



(b) Treated case
Figure 4. Instantaneous pressure fluctuations due to vortex shedding from trailing edge.

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